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ASSESSMENT OF MULTIAXIAL FATIGUE BEHAVIOUR OF CYLINDER HEAD FOR A NEW FREE PISTON LINEAR ENGINE

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ABSTRACT

This paper presents the assessment of multiaxial fatigue criteria for the cylinder head of new two-stroke free piston linear engine using the finite element analysis technique. The assessment processes were performed using the finite element analysis and fatigue analysis. The structural three-dimensional solid modeling of cylinder head was developed using the CATIA® V5R13 computer-aided drawing software. The finite element modeling and analysis were performed using the finite element analysis commercial code. Finally, the stress-strain state of the component obtained previously is employed as input for the fatigue life. In addition, the biaxiality analysis was utilized to assess the multiaxial fatigue of the cylinder head using the finite element based fatigue analysis code. The biaxiality analysis gives a good understanding of the stress state in the model and how that stress state varies with time. The biaxiality correction methods were used to correct the treatment of material properties in the application of the Neuber method in order to take into account of the biaxiality of the loading. The Material parameter or Hoffmann-Seeger methods were used to modify the uniaxial material properties. Prediction of fatigue life, effect of the stress combination for the proportional loading condition was investigated in this paper. It can be seen that the biaxiality correction method give the conservative predicted results as compared to the uniaxial loading. It is also seen that the materials parameter correction method gives the most conservative prediction with the SWT criteria. It is observed from the results that the more conservative prediction to use the Signed Tresca parameter. The Signed von Mises stress gives the result that lie between the absolute maximum principal and signed Tresca results.

Keywords: Free Piston Engine, Cylinder head, FEA Technique, Fatigue Life, Multiaxial Fatigue.

1. INTRODUCTION

The safety and durability of components has become more important than before because the sudden failure of complex systems such as automotives, aircraft, power plants and pressure vessels may cause many injuries, much financial loss and even environmental damage. Since many of these parts are subjected to repeated multiaxial loadings, fatigue evaluation becomes one of the major considerations in the design of the components of the automotive industry [1-5].

Automotive components are frequently subjected to repeated loading which may lead to their failure due to fatigue. As can be seen from the statistic, a large percentage of mechanical failure is fatigue failure. In addition, the majority of fatigue failure for the components in service is the multiaxial fatigue failure [1,3]. Therefore, understanding of fatigue failure under multiaxial loading is important to many industrial applications. Although the fatigue failure criterion for uniaxial loading have been well developed does not reach a satisfactory level. This is partly due to the complex cyclic stress-strain responses for multiaxial loading which depend on the loading path. The complex cyclic stress strain responses for multiaxial loadings are very complex and the fatigue behavior of materials and structures is very difficult to be described. Multiaxial fatigue criteria, whose aim to be reduce the complex multiaxial loading to an equivalent uniaxial loading, which are very important in the study of multiaxial fatigue [2,5]. Up to now, many researchers have proposed multiaxial fatigue criteria suitable to different materials and different loading conditions. There is not yet a universally accepted model in spite of a great number of criteria.

The cylinder head is one of the most critical components and their function is of vital importance in human safety. With the changing requirements in the automotive industry in the last decade, the cylinder head manufacturers have been taking increasing attention to lightweight designs by new materials and manufacturing technologies in contradiction to durability concerns due to the complex loading conditions on head chamber [8]. The purpose of this paper is to investigate the multiaxial fatigue behavior for the cylinder head of a new free piston engine using the finite element analysis technique. A fatigue model will be proposed suitable for the material under the loading conditions employed.

2. FINITE ELEMENT MODELING AND ANALYSIS

There are a number of safety-critical component of the free piston engine. The cylinder head is the one of the important and safety-critical components of the free piston engine [6]. A geometric model of the cylinder head of the free piston engine is considered as an example parts in this study. There are several contact areas including the cylinder block, gasket, and hole for bolt. Therefore, constraints are employed for the following purposes: (i) to specify the prescribed enforce displacements, (ii) to simulate the continuous behavior of displacement in the interface area, (iii) to enforce rest condition in the specified directions at grid points of reaction [6].

Three-dimensional model of the free piston linear engine cylinder head was developed utilizing the CATIA$^{®}$ software. A 10 nodes tetrahedral element (TET10) was used for the solid mesh. Sensitivity analysis was performed to obtain the optimum element size. These analyses were performed iteratively at different element lengths until the solution obtained appropriate accuracy. Convergence of the stresses was observed, as the mesh size was successively refined. The element size of 1.25 mm was finally considered. A total of 289142 elements and 454335 nodes were generated with 1.25 mm element length. A pressure of 7.0 MPa was applied on the surface of the cylinder head chamber generating a compressive load. A pressure of 0.3 MPa was applied on the bolt-hole surface generating a preload. This preload is obtained according to the RB&W recommendations [7]. In addition, 0.3 MPa pressure was applied on the gasket surface.

The Multi-point constraints (MPCs) were applied on the bolt-hole surface for all six degree of freedom. Multi-point constraints [8] were used to connect the parts thru the interface nodes. These MPCs were acting as an artificial bolt and nut that connect each parts of the structure. Each MPC's will be connected using a Rigid Body Element (RBE) that indicates the independent and dependent nodes [8]. The configuration of the engine is constrained by bolting between the cylinder head and cylinder block. In the condition with no loading configuration, the RBE element with six-degrees of freedom were assigned to the bolts and the hole on the cylinder head. The independent node was created on the cylinder block hole. Due to the complexity of the geometry and loading on the cylinder block, a three-dimensional finite element model was adopted as shown in Figure 1. The loading and constraints on the cylinder block are also shown in Figure 1.

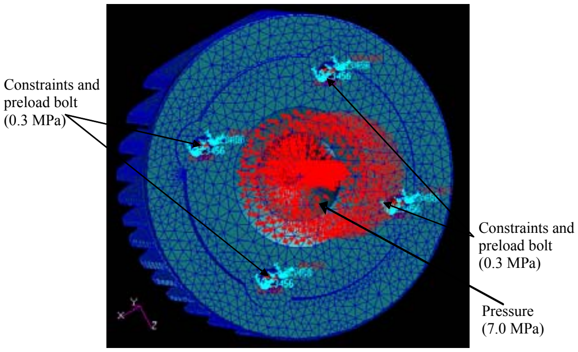

Fig 1 : Three-dimensional finite element model, loading and constraints.

Several types of variable amplitude loading history were selected from the Society of Automotive Engineers (SAE) profiles for the finite element (FE) based fatigue analysis. It is important to emphasize that these sequences are not intended to represent standard loading spectra in the same way that Carlos or Falstaf [9] was performed. However, they do contain many features which are typical of the automotive industries applications, and therefore, are useful in the evaluation of the life estimation methods. The detailed information about these histories is given in the literature [7, 12]. The variable amplitude load-time histories are shown in Figure 2. The terms of SAETRN, SAESUS and SAEBRKT represent the load-time history for the transmission, suspension, and bracket respectively.

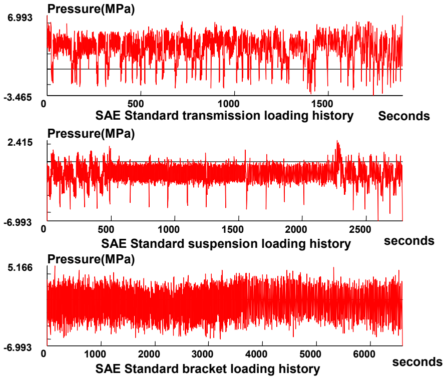

Fig 2: Variable amplitude load-time histories

The linear static analysis was performed using MSC.NASTRAN$^{®}$ finite element software to determine the stress and strain results from the finite element model. The bolt-holes areas were found to experience the highest stresses. The results of the maximum principal stresses and strains are used for the subsequent fatigue life analysis and comparisons. The maximum principal stresses distributions of the cylinder head for the linear static analysis are presented in Figure 3 for cast aluminum A356-T6 with SAETRN loading. From the acquired results, the maximum principal stresses of

642 MPa occurring at node 132171 were obtained.

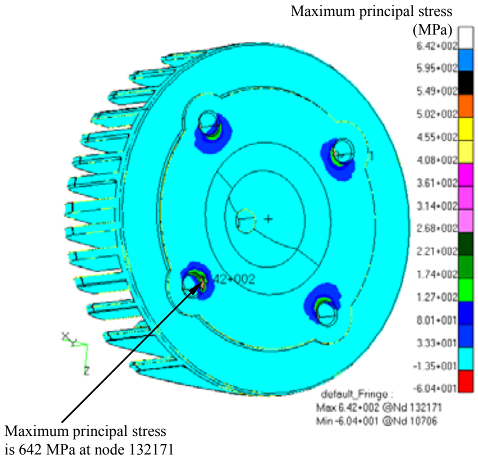

Fig 3: Maximum principal stresses contour

2.1 Identification of the Critical Locations

Figure 4 shows the absolute maximum principal stresses using the TET10 mesh. Area A experiences quite high compressive maximum stress while area B exposes to high tensile stress. From this figure it seems reasonable to assume that area B is a critical location, since cycles that are fully compressive are not expected to inflict fatigue damage. However, this figure does not reveal the magnitude of the minimum principal stress, which can has compressive cycles even if the maximum principal is in tension. This can be determined by investigating the biaxiality ratio. The average biaxiality ratio is found to be close to zero and constant in area B. It can be concluded that the uniaxial condition is prevailing at area A and multiaxial condition prevailing at area B. Therefore area B expected to have the shortest fatigue life. The figure does not indicate the stress range for the elements.

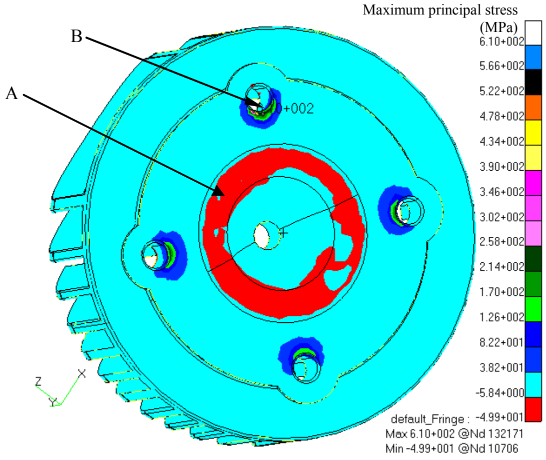

Fig 4: Identification of the critical locations of the cylinder head

Figure 5 shows the predicted fatigue life for cast aluminum ASTM A356-T6 material. The lowest observed life is $10^{5.41}$ seconds. Note that this refers to 99.8% chance of failure. However, the surface and environment condition are not considered in this analysis.

2.2 Fatigue Analysis

The fatigue life of the cylinder head is predicted using the Coffin-Manson method with the SAETRN variable amplitude loading conditions. The result of predicted fatigue life of the cylinder head corresponding to 99.8% reliability value for the cast aluminum is shown in Figure 5. The fatigue life is expressed in terms of seconds for the variable amplitude SAETRN loading histories. The fatigue equivalent unit is 3000 cpm (cycle per min) of the time history. From the results, it is observed that the predicted fatigue life of the cylinder head at the most critical location (node 132171) for the cast aluminum is $10^{5.41}$ seconds. The critical locations are also shown in Figure 5 using the SAETRN loading histories. It can be seen that the bolt-hole edge is the most critical positions for the cylinder head.

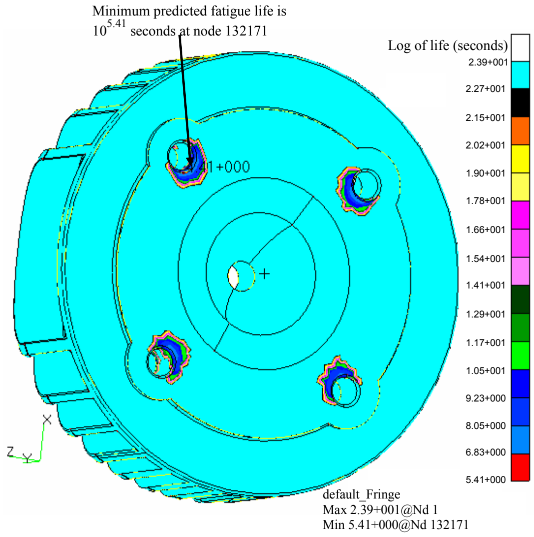

Fig 5: Predicted fatigue life contours plotted

Low weight and long lifetime are the necessary requirements for the automobiles components to significantly reduce the CO_2 emission and environmental pollutions in their operation. Aluminum alloys are one of the most promising materials selections for automobiles parts and the electrical components in order to reduce their weight and to increase their specific strength. The automotive industry has increasingly adopted aluminum as a structural alloy in order to fulfill the demands for the component safety, performance and economy. For the critical components, large safety factors are applied since the design and analysis are associated with several uncertainties. Accurate predictions are therefore essential for the weight reduction purposes and also to minimize the number of physical prototypes preferably down to one. The requirement for the accuracy prediction applies in several aspects: load history, material properties, finite element modeling and choice of fatigue assessment method. Based on these requirements, aluminum alloy component is considered in this study.

3. MULTIAXIALITY ANALYSIS

The multiaxiality analysis gives a good understanding of the stress state in the model and how that stress state varies with time [5, 9-11]. It uses the surface resolved stresses and to define as the state of stress on the surface of the model must be plane stress meaning the out-of-plane stress, must be zero. It is then used the two in-plane principal stresses to determine the biaxiality ratio, $a_e = \sigma_2/\sigma_1$, where σ_1 is the absolute maximum in-plane principal stress and σ_2 is the other in-plane principal. This parameter can take on values between minus one (pure shear) and plus one (fully biaxial). A biaxiality analysis also determine the standard deviation of the biaxiality ratio and the angle spread, that is, how the biaxiality ratio is changing over time and whether the angle, ϕ (that σ_1 makes with the local X-axis) is changing or not.

Biaxiality ratio mean parameter is the average biaxiality ratio for every time steps in the combined loading history. The mean biaxiality ratio contours are presented in Figure 6. It can be seen that the maximum mean biaxiality ratio value (0.919) close to the +1 value at critical location (node 132171), which means that the cylinder head experiences considerable equibiaxial. Based on the above mentioned reason the multiaxial fatigue solution should be considered.

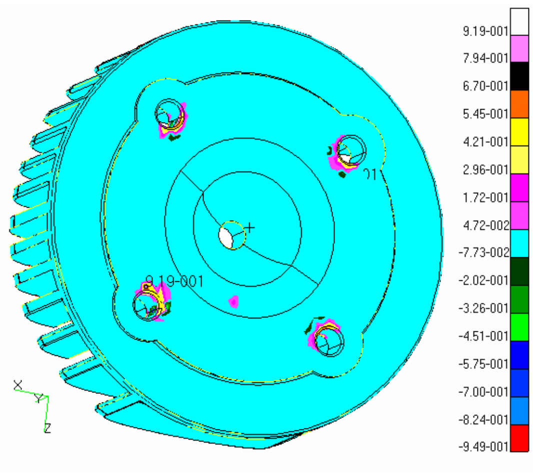

Fig 6: Mean biaxiality ratio contours

The biaxial parameters, which are calculated information to the loading multiaxiality present in the component due to the loading applied to determining the validity of the fatigue analysis. Figure 7 shows the time variation of all the multiaxiality parameters such as maximum principal stress, minimum principal stress, absolute maximum principal stress, signed von Mises stress, signed maximum shear stress for the critical location, Node 132171. The time variation of these parameters can be interesting, however the more useful plots are when each of these is cross-plotted against the principal stress for all time points. Biaxiality ratio defined as the ratio of the minimum and maximum principal stresses at a location on the surface of a component.

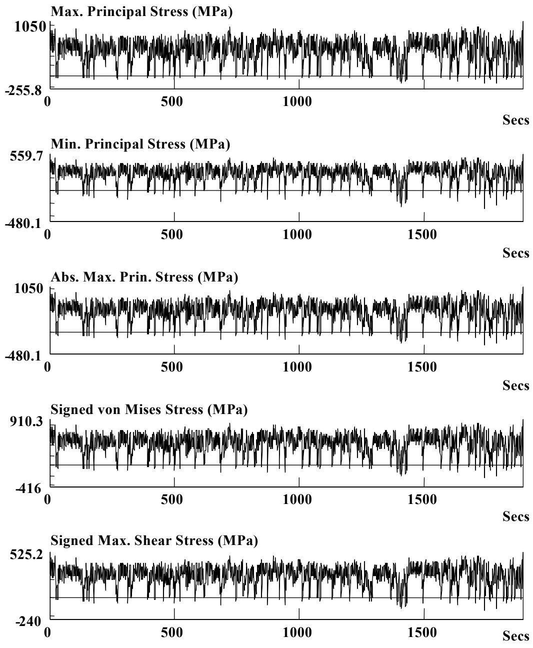

Fig 7: Time variation of all the multiaxial assessment parameters: maximum principal stress, minimum principal stress, absolute maximum principal stress, signed von Mises, signed maximum shear stress.

Figure 8 shows the cross plot of the biaxiality ratio versus the maximum absolute principal stress for the all time points at the critical location (Node 132171). The interesting thing to note is that the biaxiality ratio line up vertically at a particular ratio (0.5329) and non-zero. Figure 9 shows the cross plot of the angle versus the maximum absolute principal stress for all time points at the critical location (Node 132171). Again note that tend the angle line up vertically at a particular angle (-53.67) suggesting that the mobility is minimal and uniaxial conditions exist. The gate value (0 MPa) properly checks for mobility, which excludes small stress/strain cycles that may mislead in the interpretation of the angle spread.

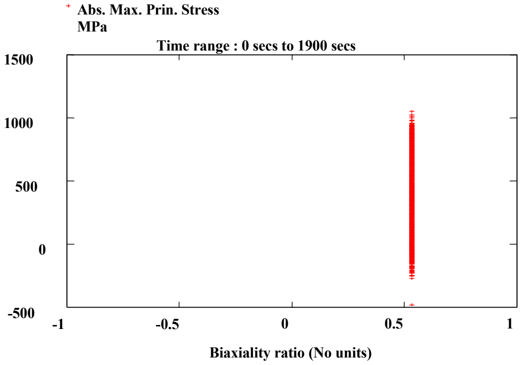

Fig 8: Cross plot of the biaxiality ratio against the maximum absolute principal stress

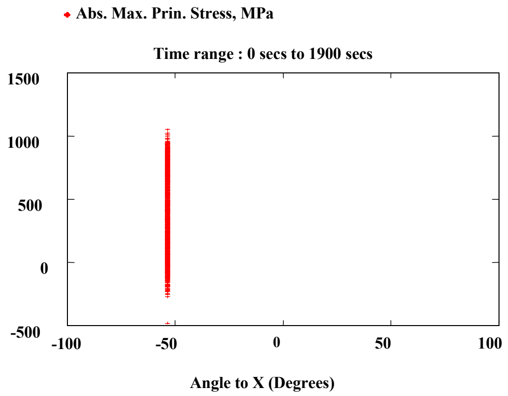

Fig 9: Cross plot of the angle against the maximum absolute principal stress

Angle distribution is shown in Figure 10. This is another way of looking at the stress tensor mobility. This plot displays the number of times each angle appeared during the loading sequence. A spike indicates the predominate angle (-53.67). Gate in stress units is the stress level below which biaxiality is ignored regardless of what the principal angles are done. The biaxiality correction method used to correct the treatment of material properties in the application of the Neuber method in order to take into account of the biaxiality of the loading. From the above discussion, this tend indicates a multiaxial proportional loading condition. Compensation can be made by using the Material parameter or Hoffmann-Seeger methods to modify the uniaxial material properties. The material parameter method basically makes a new set of parameters (E, K' and n') for each state of stress i.e. Young's modulus becomes $E^* = E/(1-\nu a_e)$, where ν is the poison's ratio. It assumes the ratio of the principal strains remains fixed and that the von Mises stress and strain yield criteria obey the cyclic stress strain curve post-yield. It is only valid to use with a maximum strain based combination such as maximum absolute principal. The Hoffmann-Seeger method makes the same basic assumptions, but makes the Neuber correction in equivalent stress-strain space. It has the advantage that it predicts all the principal stresses and strains and can therefore be used in conjunction with any equivalent stress or strain combination parameter.

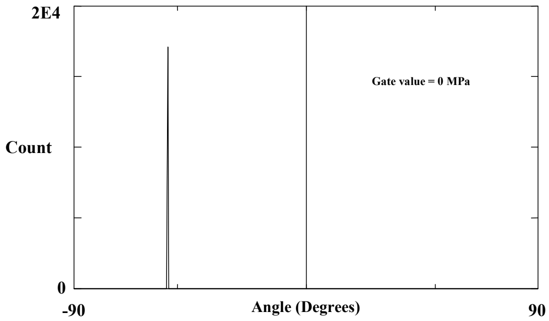

Fig 10: Distribution of the angle versus the number of times encountered throughout the time series

Table 1 lists the fatigue life in seconds using the Biaxiality correction method in conjunction with the crack initiation approach for the A356-T6 material. Examining the Table 1, it is observed that the Biaxiality correction method give the conservative results. It is also shown that the materials parameter gives the most conservative prediction with the SWT criteria. The Neuber method in conjunction with the maximum absolute principal stress is the method of choice when the mean biaxiality ratio tends to be zero. Otherwise the biaxiality is better taken into account either by using the Neuber correction in the conjunction with a yield criterion-based parameter such as Signed von Mises or Signed Tresca, or by using the Hoffmann-Seeger or the Material parameter modification method, which is listed in Table 1. Proportional loading means that no longer have a uniaxial stress state but the relative magnitude of σ_2 to σ_1 is not changing with time, i.e. remain proportional to each other. This case can also be fully handled with the basic techniques of classical durability assessment using the biaxiality correction on and possibly using a Singed Tresca Shear stress parameter as opposed to using the maximum absolute principal stress.

Table 1: Predicted fatigue life using the biaxiality correction method

Loading Cond.	**Predicted fatigue life (10^6 seconds) using biaxiality correction method**								
	No correction			**Hoffmann-Seeger**			**Material parameter**		
	CM	SWT	MO	CM	SWT	MO	CM	SWT	MO
SAETRN	0.28	0.19	0.23	0.24	0.19	0.22	0.20	0.15	0.21
SAESUS	48.7	76.4	67.6	37.1	63.0	56.9	33.2	63.9	56.7
SAEBKT	3.20	2.94	3.14	3.13	2.95	3.04	2.97	2.72	2.80

where, CM = Coffin-Manson method; MO= Morrow's method

It is observed from the results in Table 2 for the case of $a_e \leq 1$, better and more conservative prediction to use the Signed Tresca parameter. The Signed von Mises stress tends to give results that lie between the absolute maximum principal and signed Tresca. Table 3 lists the predicted fatigue life in seconds for a set of aluminum alloys using the biaxiality material parameter correction, SAETRN loading, singed Tresca and SWT parameter criteria. Examining the data from the Table 3, it shows that the AA7175-T73 alloy is the most superior material having with the longest life among the aluminum alloys while the AA6951-T6 found to be the weakest material.

Table 2: Effect of the stress combination using the biaxiality correction for SAETRN loading

Stress combination method	Prediction fatigue life (10^6 seconds) using biaxiality correction method for A356-T6 material					
	Hoffmann-Seeger method			Material Parameter correction method		
	CM	SWT	MO	CM	SWT	MO
Absolute maximum principal	0.238	0.185	0.217	0.202	0.148	0.210
Signed von Mises	0.221	0.176	0.199	0.182	0.139	0.177
Signed Tresca	0.208	0.171	0.187	0.168	0.117	0.154

Table 3: Predicted fatigue life for various materials using the biaxiality material parameter correction for the SAETRN loading, singed Tresca and SWT parameter criteria

Materials name (Aluminum alloys	Predicted fatigue life (10^5 seconds)
2014-T6-CF	2.72
5083-87-CF	1.81
5454-none-CF	2.04
6009-T6	1.12
6061-T6-80-CF	1.89
6061-T91	1.99
6070-T6	1.59
6151-T6	1.02
6262-T9	1.92
6951-T6	0.59
6061-T6-NONE-CF	3.29
7175-T73	4.79
A356-T6	1.17

4. CONCLUSION

A life prediction methodology for variable amplitude multiaxial proportional loading conditions has been developed in this work. The main objective of this paper was to propose a computational scheme for fatigue design of structural components made of typical cylinder head of free piston engine. The proposed fatigue life prediction methodology was based on the local strain-life approach and used available models. Fatigue life and crack initiation locations of an aluminum alloy cylinder head in biaxial analysis are presented for various loading conditions and different aluminum alloys. It concluded from the results that Signed Tresca, SWT criteria and SAETRN loading conditions gives the conservative prediction for materials parameter biaxiality correction method. Conventional multiaxial fatigue damage criteria (like von Mises) based on the equivalent stress or strain has made nonconservative life predictions under proportional multiaxial loading.

5. ACKNOWLEDGMENT

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